Neutron β-Decay and Precision Tests of the Standard Model

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The neutron, the simplest nucleus that undergoes β-decay, is an ideal system with which to study the weak interactions of the Standard Model. In neutron β-decay, the neutron, made up of three quarks (*udd*), decays to a proton (*uud*), an electron (also called a beta particle), and an electron antineutrino: $n \rightarrow p + e^{-} + \bar{\nu}$ an antineutrino. At the quark level, one of the *d* quarks in the neutron decays to a *u* quark inside the neutron, emitting a *W* particle, which further decays into an electron antineutrino and an electron. The transformation of the *d* quark into a *u* quark inside the neutron creates a particle made up of *uud*, which is a proton.

In the Standard Model, the neutron β-decay process can be described using very few parameters. By performing precision measurements on various aspects of this decay, one can determine values for those fundamental parameters that best describe the experimental results. They can then be compared with or combined with the parameter values that best describe other processes governed by the same weak force. In this way, one can perform precision tests of the validity and consistency of the Standard Model.

One test of consistency is to check that the experimental values for the elements of the CKM (Cabibbo-Kobayashi-Maskawa) matrix maintain the unitarity of the matrix. The CKM matrix is a set of nine numbers that describes the mixing between the mass and the weak eigenstates of the quarks. These numbers can be determined by measuring the rate at which hadrons (particles made of quarks and/or antiquarks) undergo weak decay (for example, the rate of neutron β-decay) and comparing that to the decay rate of the muon. Testing to see if the CKM matrix is unitary, in particular, whether it satisfies the condition

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \qquad (1)$$

tests various aspects of the Standard Model, including the following: the possible existence of more than three generations of quarks, the validity of the quark-lepton universality of the strength of the charged weak interaction, and the existence of possible new physics through the small radiative corrections that need to be applied in extracting the CKM elements from the observed decay rates of hadronic systems and the muon.

The value of $|V_{ud}|$ can be determined from the *A* coefficient in neutron β-decay (which characterizes the angular correlation between the neutron spin and the direction into which the electron is emitted) and the neutron lifetime. As seen in Figure 1, the value of $|V_{ud}|$ determined in that way has a large uncertainty because of widely varying values of λ deduced from measuring *A*. In addition, the most recent and precise result for $|V_{ud}|$ (deduced from the Perkeo II measurement of β) disagrees with the gray band, the value predicted when the experimental results for $|V_{us}|$ and $|V_{ub}|$ determined from kaon decay and *B*-meson decay are inserted in the unitarity condition—Equation (1). Furthermore, those two values of $|V_{ud}|$ are inconsistent with the result for $|V_{ud}|$ from nuclear β-decay. It is not clear whether these discrepancies are caused by some erroneous measurements or by some new physics. A measurement of *A* with a much higher precision ($\delta A/A \sim 0.2$ percent) is needed to resolve this situation.

New Approach—Ultracold Neutrons

All previous measurements of *A* were done using beams of cold neutrons from nuclear reactors. These neutrons have velocities of a few hundred to several hundred meters per second (m/s), or temperatures of a few tens of kelvins. In general, these experiments have the following problems: (1) the halo in the beam acts as background radiation; (2) the supermirror used to polarize the neutrons is basically magnetized iron and therefore acts as an additional source of gamma-ray background; (3) the supermirror polarizer typically limits the neutron polarization to 98–99 percent. Most of these difficulties can be overcome by using ultracold neutrons (UCNs) instead of cold neutrons. Ultracold neutrons have velocities less than 8 m/s (which correspond to millikelvin temperatures). Having such low velocities,

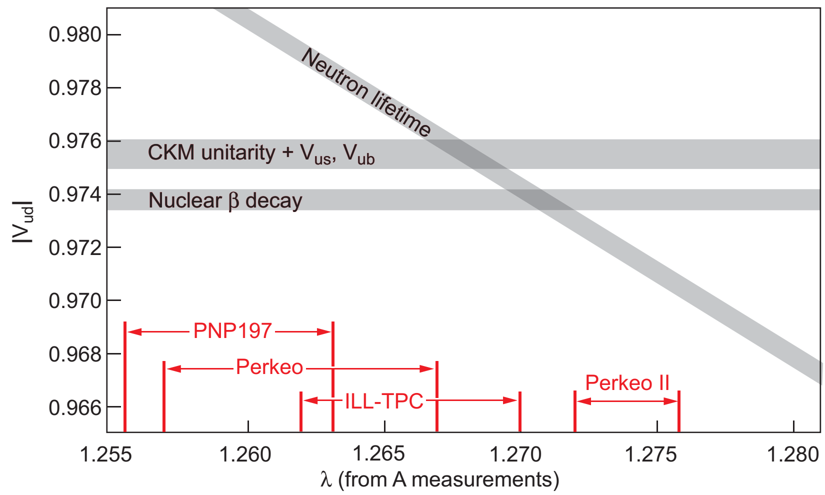

Figure 1. Current Experimental Status of the Determination of $|V_{ud}|$
The measurements of the *A*-coefficient in neutron β-decay determine the value of λ, the ratio of two different nucleon coupling constants of the weak interaction. The results from four recent experiments are shown by the four brackets along the λ axis. The combination of a λ-measurement (or *A*-measurement) and a neutron lifetime measurement determines the value of $|V_{ud}|$. Also shown are the $|V_{ud}|$ determination from nuclear β-decay and the $|V_{ud}|$ determination from kaon and *B*-meson decays and the assumption of CKM unitarity. Currently, nuclear β-decay provides the most precise experimental determination of $|V_{ud}|$. However, it is inconsistent with the value obtained from kaon and *B*-meson decays and the assumption of CKM unitarity. In principle, neutron β-decay can provide a theoretically cleaner determination of $|V_{ud}|$ than nuclear β-decay. However, the value of $|V_{ud}|$ determined from neutron β-decay has a large uncertainty because of the large uncertainty in the value of λ. In addition, the most recent (and most precise) λ-measurement (Perkeo II) yields a value of $|V_{ud}|$ inconsistent with the values from two other methods.

they can be totally externally reflected from the surface of selected materials. Therefore, it is possible to transport UCNs over long distances and store them in an area well shielded from background radiation. In addition, with such small velocities, the potential energy associated with the interaction of the magnetic moment of the neutron can easily be made comparable to the kinetic energy of the neutron. Therefore, by simply passing neutrons through a region with a large magnetic field (>6 teslas), one can filter out neutrons with one spin state, thereby making them 100 percent spin-polarized. Such properties of UCNs allow designing and performing a much improved *A*-coefficient measurement.

Solid-Deuterium Superthermal UCN Source

The traditional approach to the production of UCNs was to obtain neutrons from a reactor and cool them down by passing them through a moderator such as liquid hydrogen. The principal difficulty with such an approach is that neutrons from reactors typically have energies 13 orders of magnitude higher than UCNs, and even the neutrons that are cooled by the moderator have energies 4 orders of magnitude too high. Therefore, the fraction of neutrons that have low enough velocities to be UCNs is very small, about 1 in a million even in the case of neutrons cooled by a 20-kelvin liquid-hydrogen moderator.

A new approach adopted by a team of physicists from Los Alamos and other institutions for the new UCN source at the Los Alamos Neutron Science Center (LANSCE) is (1) to use neutrons from a spallation source and (2) to cool the neutrons through a superthermal process that uses solid deuterium as the moderator (Figure 2). In a spallation neutron source, a beam of protons from an accelerator strikes a target made of heavy metal such as tungsten, and neutrons are knocked out and boiled off from the atomic nuclei. By operating the accelerator in a pulsed mode, one can limit the emission of background radiation, which interferes with precision measurements, to the period in which the beam pulse strikes the target. This is a big advantage of spallation sources over reactor sources, which generate continuous background radiation. In the superthermal process, the modera-

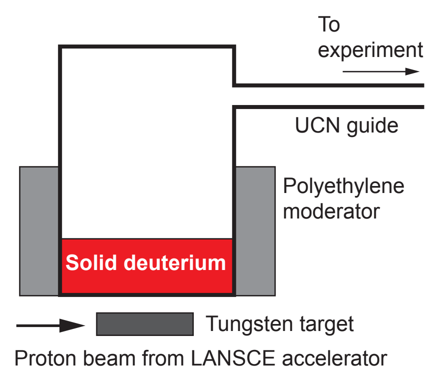

Figure 2. Schematic of the LANSCE Spallation-Driven Solid-Deuterium Superthermal Source
The neutrons are produced by spallation when the LANSCE 800-MeV proton beam strikes the tungsten target. Then the produced neutrons are "cooled" by the cold polyethylene moderators and then further cooled by the superthermal process in solid deuterium to become ultracold. The UCNs are guided to the experiment through the UCN guides.

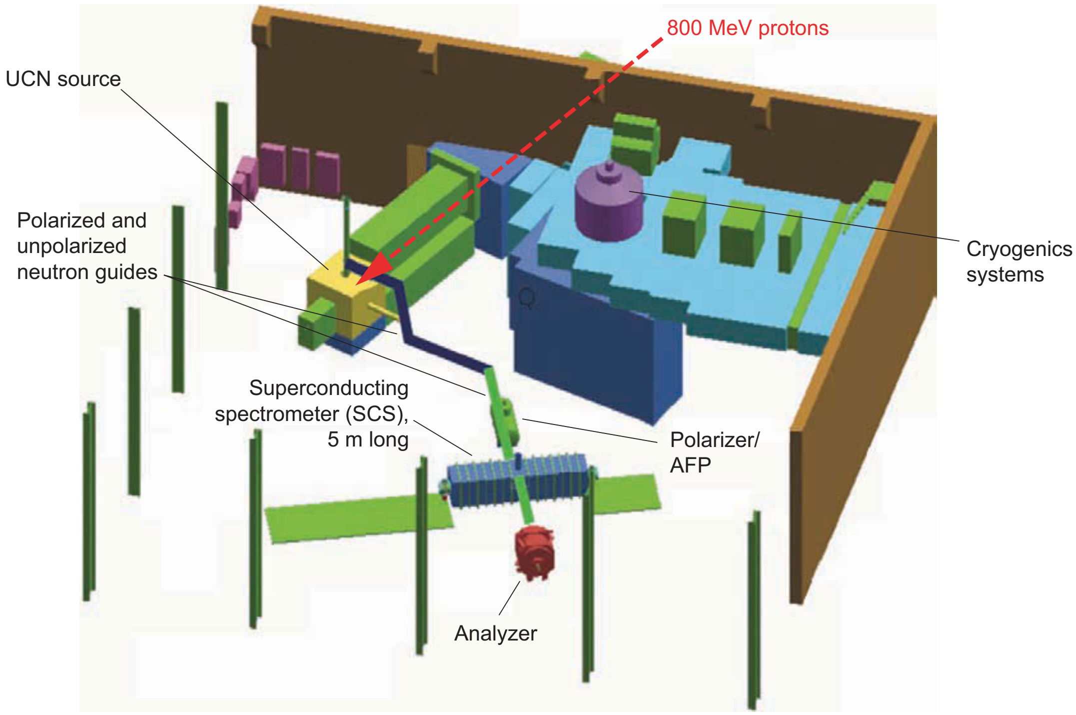

Figure 3. Schematic of the UCNA Experiment in Area B
UCNs are produced in the spallation-driven solid-deuterium superthermal source by the 800-MeV proton beam from the LANSCE linac. UCNs are guided to the experiment through the UCN guides. UCNs are polarized by going through a 7-T magnetic field and are then sent to the decay volume in the superconducting spectrometer (SCS). The neutron spin can be flipped by adiabatic fast passage (AFP). The superconducting coils create a 1-T magnetic field in the decay volume, which serves as the holding field for the neutron spin and as the guiding field for the electrons. The electrons from neutron decay are guided toward the electron detectors mounted at each end of the decay volume.

tor and the neutrons do not come to a thermal equilibrium. Rather the input flux of cold neutrons is efficiently converted to UCNs by exciting vibrations (phonons) in the solid deuterium. The reverse process, whereby a UCN absorbs energy from a phonon, can be suppressed by keeping the temperature of the deuterium relatively low (~5 kelvins). To demonstrate that this UCN production mechanism indeed works, we have built a prototype UCN source and used it to achieve the world record for the UCN density: approximately 140 UCNs per cubic centimeter.

The UCNA Experiment

The UCNA experiment aims to measure the *A*-coefficient with a precision of 0.2 percent (Figures 3 and 4). In general, *A*-coefficient measurements are performed by letting spin-polarized neutrons decay in a volume in the presence of a uniform magnetic field and counting the number of decay electrons emitted parallel, N_+, and the number emitted antiparallel, N_-, to the neutron spin. The asymmetry, which is the difference of the two divided by the sum, is related to the *A* coefficient, as shown in the following expression:

$$\text{Asymmetry} = (N_+ - N_-)/(N_+ + N_-) = A\beta P/2 \quad , \qquad (2)$$

where β is the electron's velocity and *P* is the degree of spin polarization of the neutron. As can be seen from this expression, it is important to determine the degree of neutron polarization with high precision to obtain the value of *A* with high precision. Also, in order to determine the value of the asymmetry reliably, it is important to minimize the background in the electron detector.

As mentioned above, UCNs produced by the spallation-driven solid-deuterium superthermal source at LANSCE provide a high degree of neutron spin polarization and a low-background environment. In addition, this experiment has various new features, including very sensitive, multiwire, proportional chambers that complement plastic scintillation detectors for electron detection. In the previous experiments, one serious source of uncertainty was a class of events in which the decay electron is emitted in one direction, strikes the detector in that direction, gets bounced back by it, and gets detected by the other

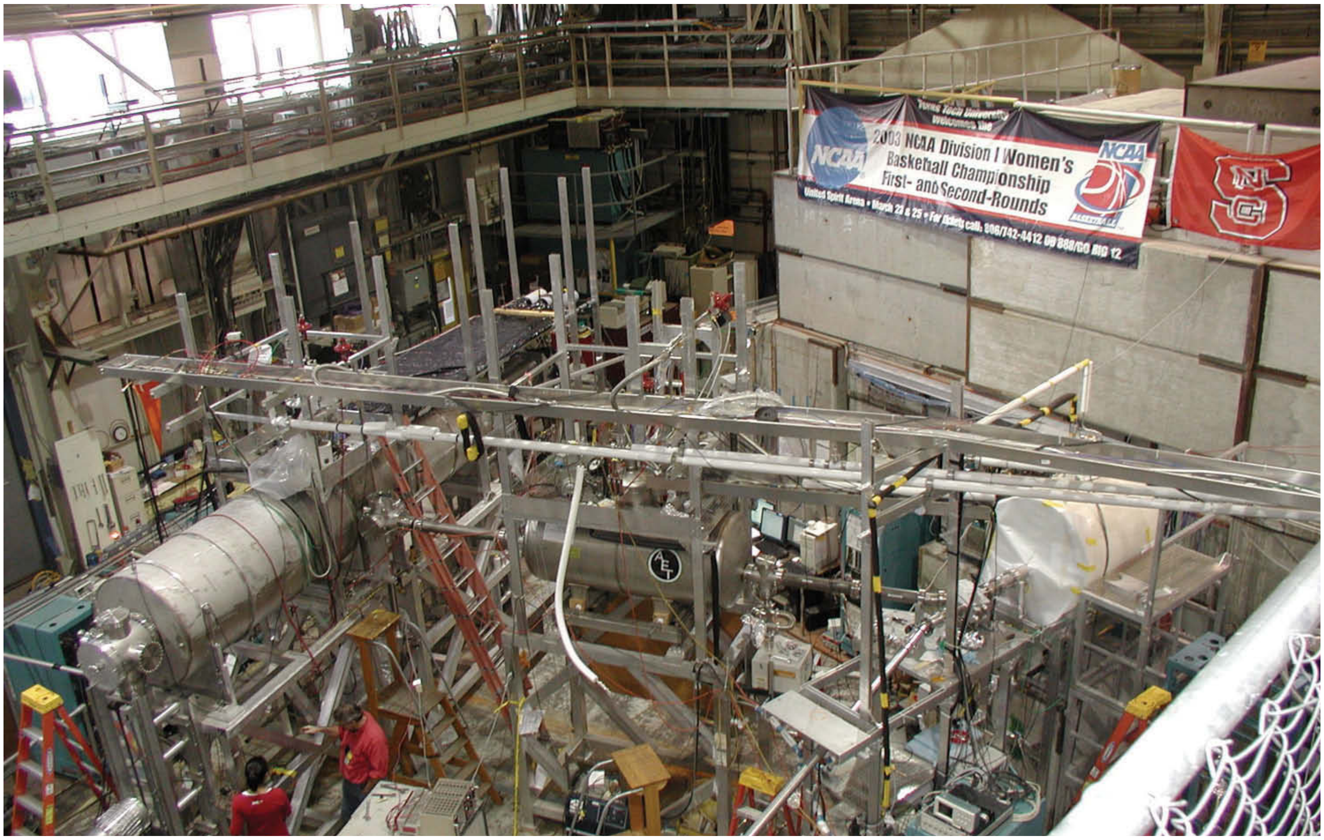

Figure 4. The UCNA Experiment in Area B

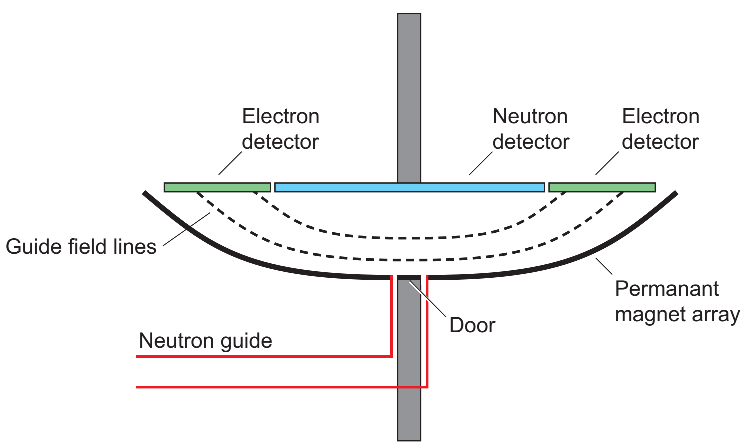

Figure 5. Schematic of the LANSCE Neutron Lifetime Experiment
Neutrons are trapped in vacuum in a tub-shaped trap by magnetic and gravitational fields. Permanent magnets covering the bottom of the trap provide the magnetic field. The trap design forces the motion of the neutrons to be chaotic to eliminate quasistable trajectories. The detector array is lowered periodically to absorb any neutrons that have enough energy to leave the trap.

detector. Obviously, if the electron leaves a signal below the detection limit on the first detector, we are led to an erroneous value for the asymmetry in Equation (2). The use of multiwire proportional counters, which are far more sensitive to small signals than plastic scintillators, will help us reduce the uncertainty in measuring the asymmetry in Equation (2).

This experiment is currently under commissioning at Area B of LANSCE. We plan to start taking physics data in 2006.

A New Neutron Lifetime Experiment at LANSCE

The neutron lifetime is a key input in determining the value of $|V_{ud}|$ from the neutron decay (Figure 1). In addition, it has an important implication for understanding Big-Bang nucleosynthesis, the production of various nuclear elements in the early universe.

In general, to measure the lifetime of a subatomic particle, one needs to measure either the intensity of the decay products emitted from a sample of the particles in question or the exponential decay of the emission rate of the decay products (which is equivalent to the exponential decay of the number of surviving particles). For the first approach, one needs to know the number of particles in the sample. For the second approach, one needs to ensure that radioactive decay is the only mode by which particles in the sample are lost. The fact that the neutron has no electric charge makes either approach very challenging. In the first approach, measuring the intensity of the decay products, one typically uses a beam of neutrons as the sample (beam method), but knowing the number of neutrons has proved to be a major challenge because it is very difficult to measure the neutron beam intensity accurately. In the second approach, measuring the exponential decay of the emission rate or the number of surviving particles, one typically traps the neutrons in a material bottle (trapping method), but controlling and understanding neutron loss caused by the material wall interaction has been a daunting task.

It is possible, however, to trap neutrons without a material bottle by using the magnetic force and/or the gravitational force. In an inhomogeneous magnetic field, neutrons feel a force that pushes them either toward or away from a region with stronger a field depending on the orientation of spin. By arranging the magnetic field so that it becomes stronger as one goes away from the center of the trap, one can trap neutrons at the center because the magnetic force pushes them toward the weaker field region. The trapped neutrons do not interact with any material, and hence β-decay is the only mechanism through which the trapped neutrons can disappear.

In a new lifetime measurement currently under development at LANSCE, neutrons will be trapped in vacuum in a trap made of magnetic and gravitational fields (Figure 5). The arrays of permanent magnets covering the tub-shaped surface at the bottom of the trap provide the magnetic field, which falls off exponentially as the distance from the surface. This magnetic field provides the force to trap neutrons horizontally and the force to keep the neutrons from escaping from the bottom of the trap. Gravity provides the force to keep the neutrons from escaping from the top of the trap. The solid-deuterium UCN source will be used as the source of neutrons. The electrons from neutron β-decay will be guided by the magnetic field lines toward the electron detectors.

This experiment is notable for its ability to address the issue of marginally trapped neutrons. Marginally trapped neutrons have enough energy to leave the trap but are following quasistable orbits and may therefore remain in the trap for times comparable to the neutron lifetime. Such neutrons can cause the measured lifetime to deviate from its true value by providing an extra mechanism through which neutrons in the trap can disappear. In this experiment, this loss mechanism is prevented by the "chaotic-cleaning" method. The trap is designed in such a way that the motion of the neutrons in the trap is chaotic to eliminate quasistable trajectories. During the cleaning period of the experiment, the detector array is lowered so that any neutrons that have enough energy to leave the trap are forced to collide with the detector array and be absorbed in 2 to 3 seconds.

Once the solid-deuterium UCN source reaches its full potential, a neutron lifetime measurement with an accuracy of 10^{-4} is possible with this apparatus. ■

Further Reading

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